the Energy to Lead

Hybrid Membrane/Absorption Process for Post-Combustion CO_2 Capture (Membrane Contactor)

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Outline

- Introduction of GTI and PoroGen
- Project Overview
- Fundamentals of Membrane Contactor Technology
- Project Objectives and Approach
- Plan and Summary

Facilities & Staff

> Main Facility:

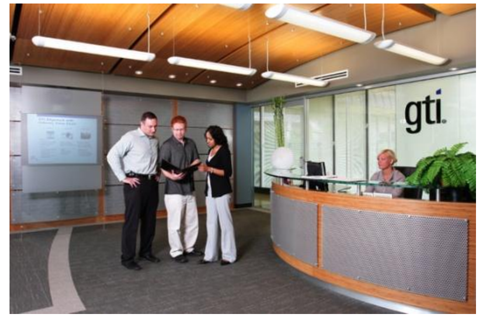
18-Acre Campus

Near Chicago

- Over 200,000 ft^2 of laboratory space
- 28 specialized laboratories and facilities

> Staff of 250

- 70% are scientists and engineers
- 45% with advanced degrees



Offices & Labs

Flex-Fuel Test Facility

Energy & Environmental Technology Center

Specific GTI Programs Related to CCS

- R&D on membrane contactor (Carbo-Lock™) Technology for pre-. and post-combustion CCS
- Morphysorb® for pre-combustion CO_2 capture, natural gas CO_2 removal
- U-Gas® fluidized-bed coal or biomass gasification
- Wood gasification (to liquid transportation fuels) and gas cleanup
- Selective removal/recovery of H_2S from syngas (UCSRP)
- CO_2 to Biomethane (Algae)
- Regional Partnership for Carbon Capture (SW and Midwest Partnerships)
- Reservoir monitoring and site selection

PoroGen Technology

- Material technology company
- Building products manufactured from specialty high performance plastic PEEK
- Core of PoroGen’s patented technology is porous PEEK materials
- Diverse line of products ranging from membrane fluid separation filters to heat transfer devices
- Module area up to 1000 ft2 and module diameter from 2 to 12 inches

Project Overview

Overall Budget

- Total Budget: $3,736 K
  - Federal $2,986 K
  - Cost Share $750 K
    - ✓ ICCI $375K
    - ✓ Midwest Generations $225K
    - ✓ PoroGen $150K
- Performance Date
  - Oct. 1, 2010 – Sept. 30, 2013

Performing Organization and Key Staff

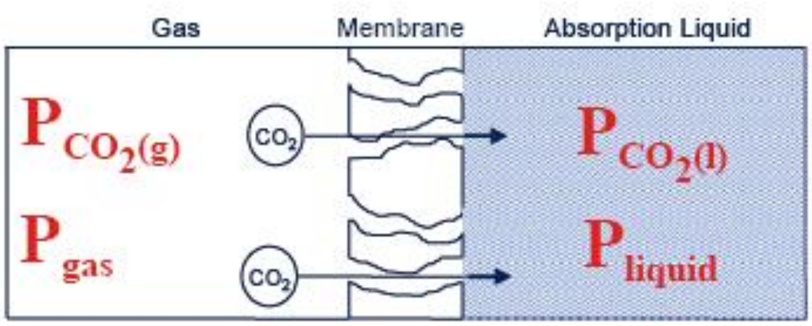
- Gas Technology Institute
  - Jim Zhou as PI, Howard Meyer as PM
  - Working on process development and testing
- PoroGen
  - Ben Bikson and Yong Ding
  - Working on membrane and membrane module development
- Aker Process Systems
  - Pal Nokleby
  - Working on membrane process modeling and economic analysis
- Midwest Generations EME, LLC
  - Kent Wanninger
  - Pilot test site

Fundamentals of Membrane Contactor Technology

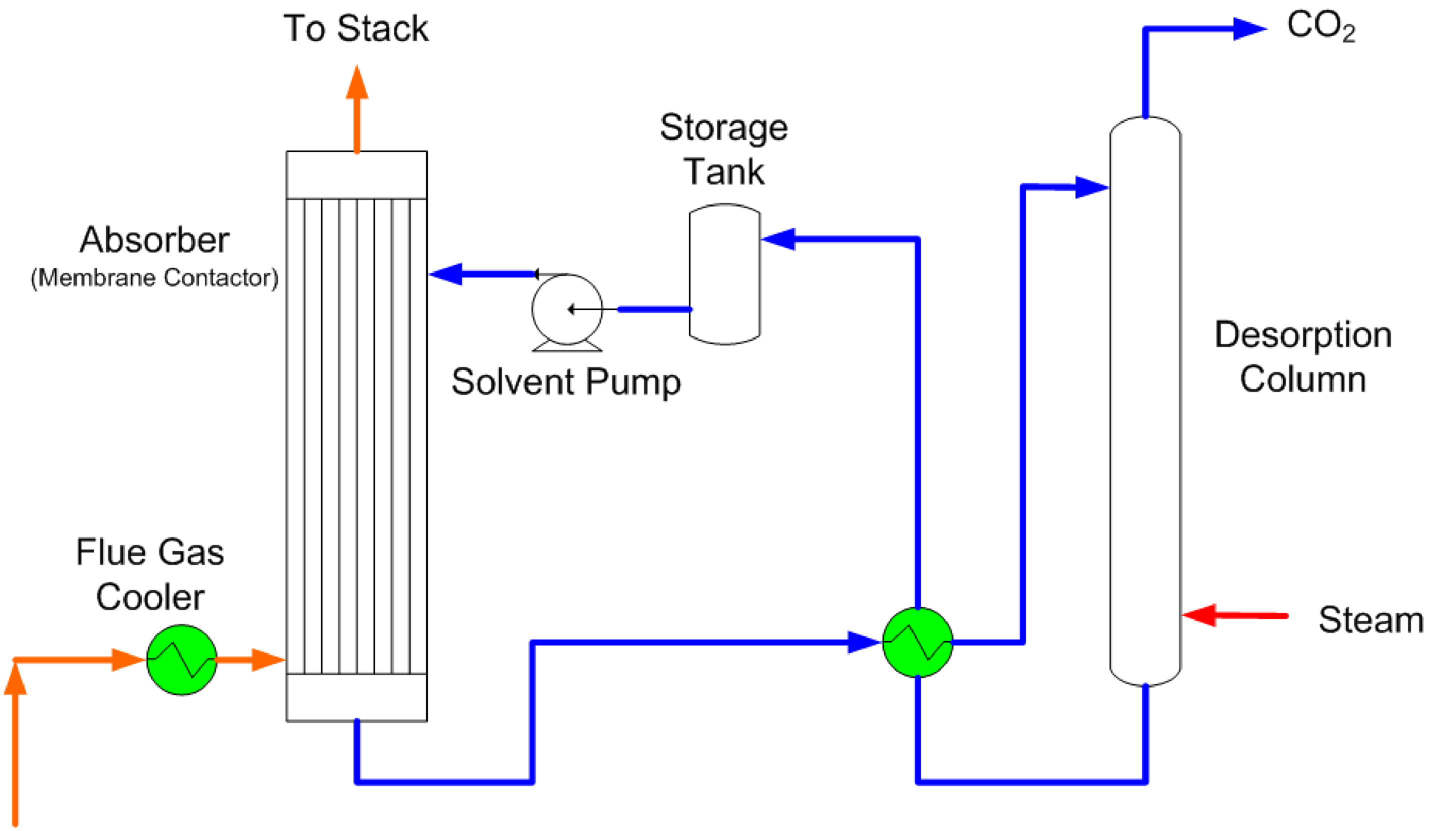
Basic Principles

Membrane mass transfer principle

- Porous, hollow fiber membrane
- Unique membrane material, PEEK
- Membrane matrix filled with gas
- Mass transfer by diffusion reaction
- Driving force: difference in partial pressures of component to be removed/absorbed ($PCO_2(g)>PCO_2(l)$)
- Liquid on one side, gas on the other side of the membrane
- Pressure difference between shell and tube side almost zero
- ($P_l \geq P_g$), i.e. the mass transfer is not pressure driven



Process Description



Flue Gas

Afft FGD 40 to 80 C
16 to 20 psia

General Approach

Hybrid membrane/solvent absorption process

- Nano-porous, superhydrophobic PEEK hollow fiber membrane
- Increases interfacial gas/liquid contact area 10x over conventional packed or tray columns — increases overall mass transfer coefficient
- Selectivity controlled by solvent chemical affinity
- Low steam regeneration energy
- CO_2 can be generated at pressure
- Planned slipstream test at Midwest Generation's Joliet Power Station (Size: 25 kWe)

Process Features

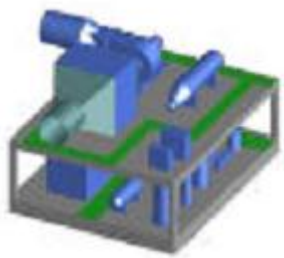
- The gas/liquid contactor is a hybrid between membrane and the conventional absorption processes.

Process features:

- Higher CO_2 loading differential between rich and lean solvent is possible
- Increased mass transfer reduces system size
- High specific surface area available for mass transfer
- Independent gas and liquid flow
- Linear scale up
- Concentrated solvents or specialty absorbents can be used
- Conventional and developmental solvents

Benefits of Membrane Contactor Process

Conventional Amine Scrubber Column



Carbo-Lock™ Membrane Contactor

Membrane Advantages:

- **Capital Cost (CapEx) 35%**
- **Operating Costs (OpEx) 40%**
- Dry Equipment Weight 35%
- Operating Equipment Weight 37%
- Total Operating Weight 47%
- Footprint Requirement 40%
- **Height Requirement 60%**

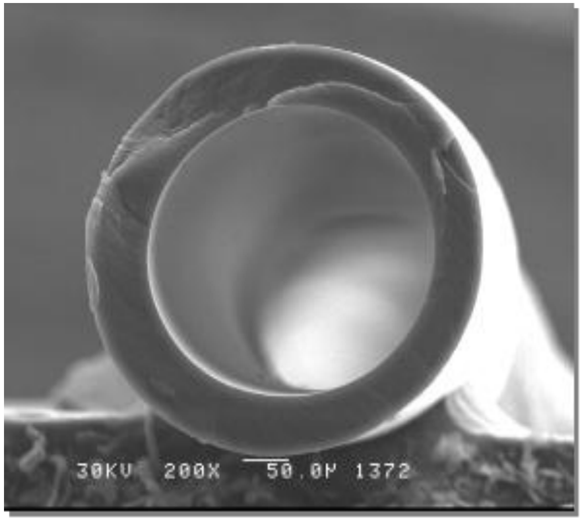
*Data by Aker Kvaerner

Previous Work – ePTFE

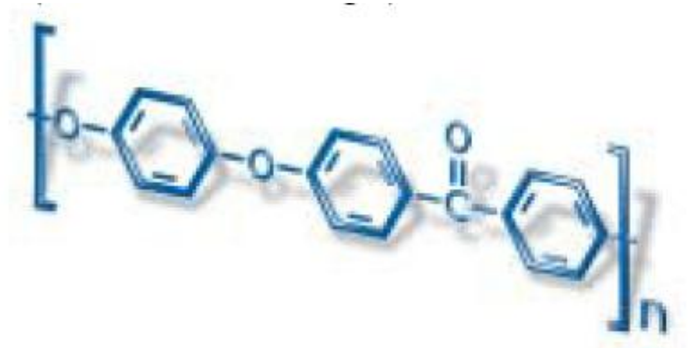
- GTI worked closely with Kvaerner (now Aker) on ePTFE based membrane contactor process development
- This project was successful technologically
  - ✓ ePTFE system was found to have high mass transfer rate
  - ✓ Resulted in up to 75% reduction in volume and 65% reduction in weight
- GTI worked with Kvaerner, Duke Energy, and Chevron on membrane contactor field tests for dehydration
  - ✓ Successfully demonstrated the technology
- Wetting of pores observed resulting in solvent loss and loss of productivity
- Process economics was high due to
  - ✓ High cost of ePTFE membrane module per attainable performance
  - ✓ High cost of pressure control system

Membrane Material Properties of PEEK

- Very high heat resistance
- High rigidity
- High dimensional stability
- Good strength
- Excellent sliding friction behavior
- Excellent chemical resistance
- Excellent hydrolytic stability
- Average pore size 1 to 50 nm
- Average porosity 40 to 70%
- 800 psi water breakthrough pressure



PEEK Hollow Fiber



PEEK can operate continuously in contact with aggressive solvents.

Technology Challenges

- Long-term membrane wetting in contact with solvent
  - By membrane surface treatment
  - By making composite membrane with non-porous coating
- Membrane contactor mass transfer coefficient
  - By optimizing of membrane physical properties
  - By optimizing membrane module physical properties
- Process cost
  - By reducing membrane cost itself through gradual maturity of the technology and large scale production
  - By reducing energy cost of solvent regeneration through novel regeneration methods and deployment of new solvents

Performance Characteristics

- Tests were performed with a variety of absorbents including carbonate solution and amine solvents.

Example: Potassium Carbonate Solution and amines
Inlet P =6 psig
Gas T = 25 C
Liquid T = 50 C

N_2, kmol/m²/hr	$K_G a$, kmol/(m³.hr.kPa)	GPU Equivalent	Solvent
35.27	0.21	3200	K_2CO_3 20 wt%
34.42	0.56	3512	Amine Solvent
48.02	0.94	4910	Amine Solvent

Process Economics Analysis

CCS economics for pulverized coal power plants

Basis	Pulverized Coal Boiler		
	DOE PC Subcritical		PC Subcritical with Membrane Contactor and KS-1 solvent
	Case 9 [c]	Case 10 [c] (MEA)	
CO_2 Capture	No	Yes	Yes
Gross Power Output (kWe)	583,315	679,923	625,000
Auxiliary Power Requirement (kWe)	32,870	130,310	75,000
Net Power Output (kWe)	550,445	549,613	550,000
LCOE (mills/kWh) [a]	64.0	118.8	91.0 [b]

[a] **Based on an 85% capacity factor**
[b] **Value is based on membrane cost of $\$100/m^2$**
[c] **Case 9 and 10 are from** "Cost and Performance Baseline for Fossil Energy Plants," DOE/NETL-2007/1281

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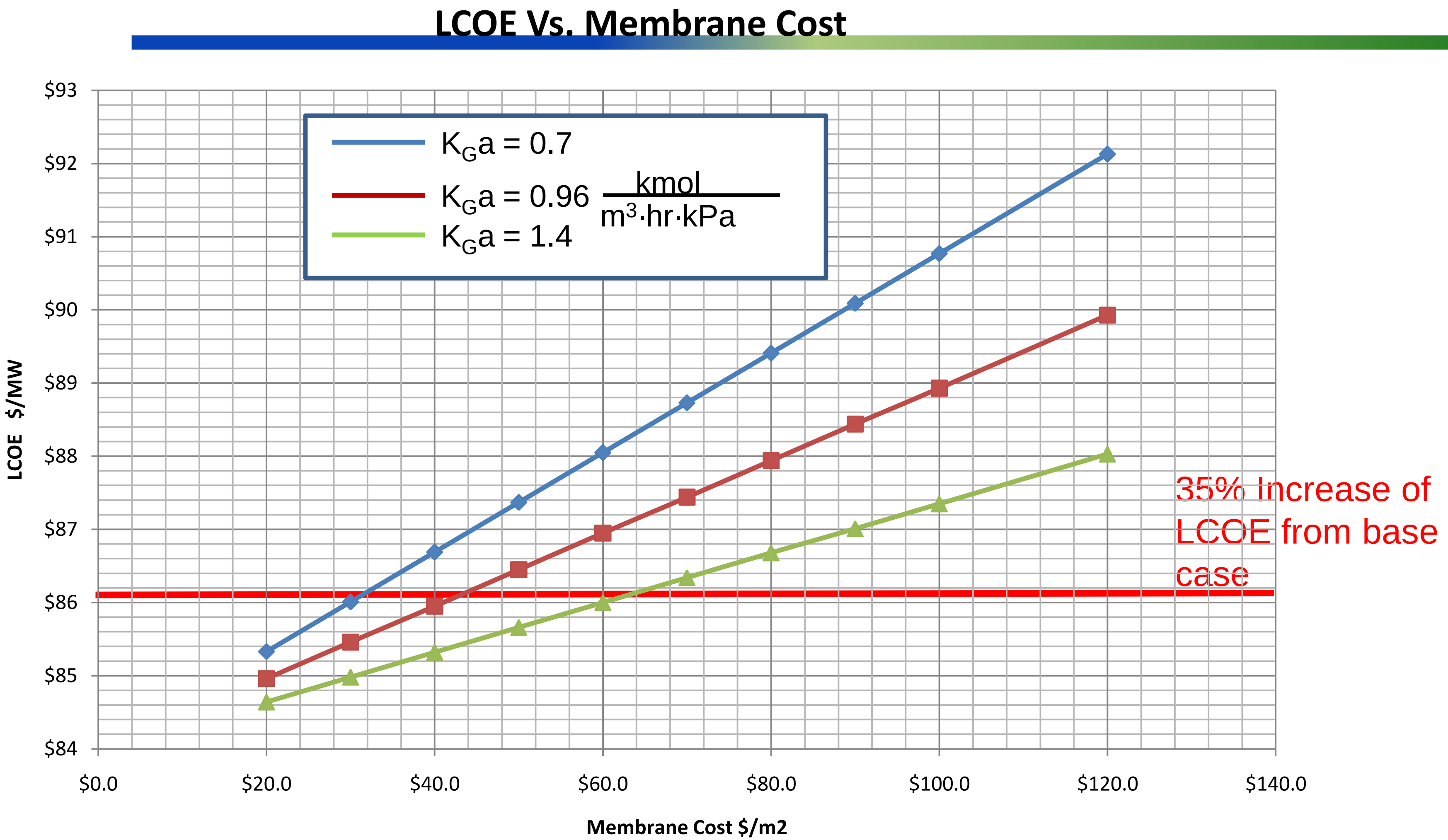
Sensitivity Analysis of LCOE



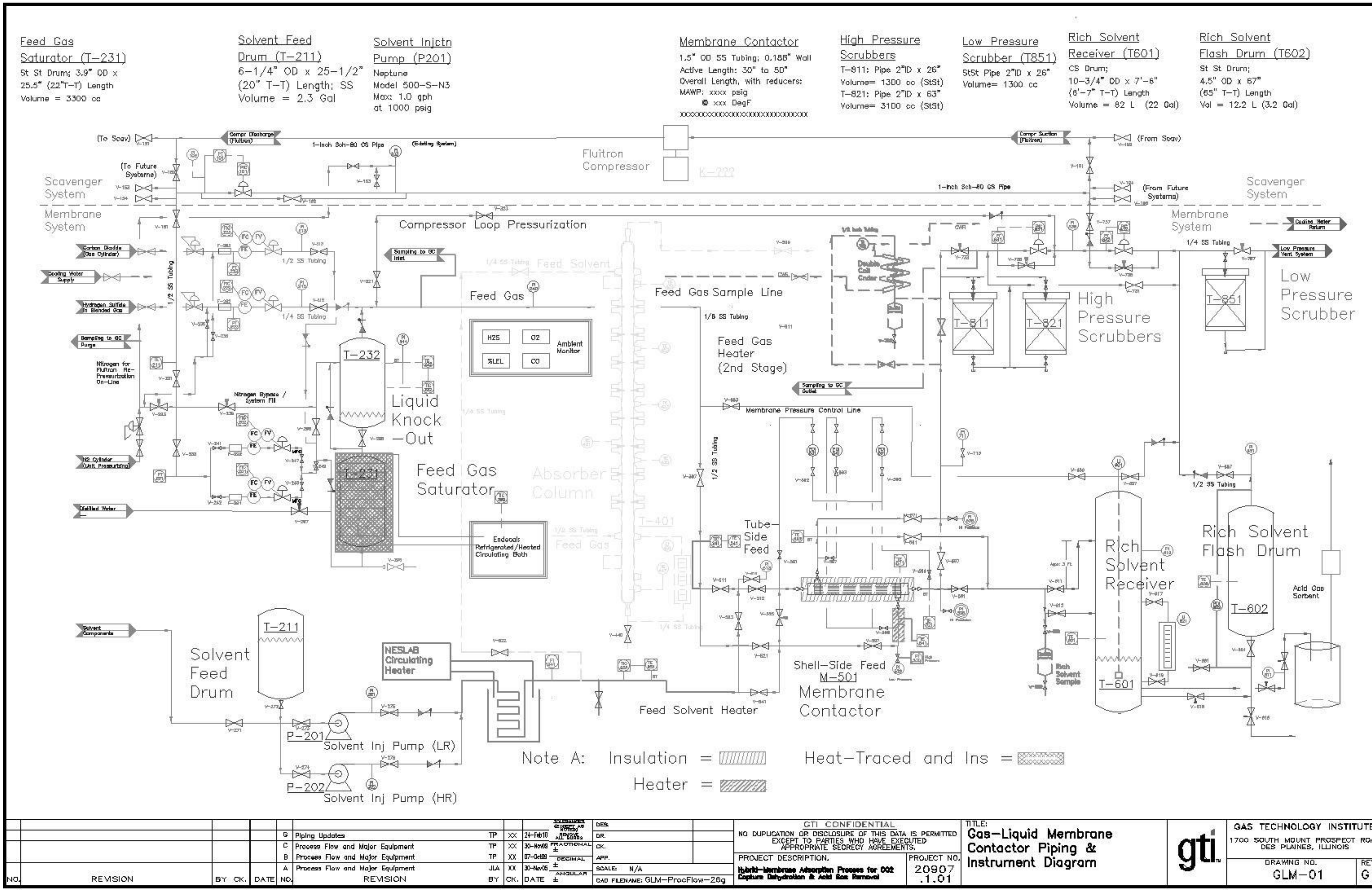
Project Objectives and General Approaches

Objectives

> Overall objective: To develop cost effective separation technology for CO_2 capture from flue gases based on a hollow fiber membrane contactor technology

1. A highly chemically inert and temperature stable PEEK hollow fiber membrane for contactors
2. Integrated membrane absorber and desorber, and,
3. An energy efficient process for CO_2 recovery from the flue gas

Lab Membrane Test Unit P&ID

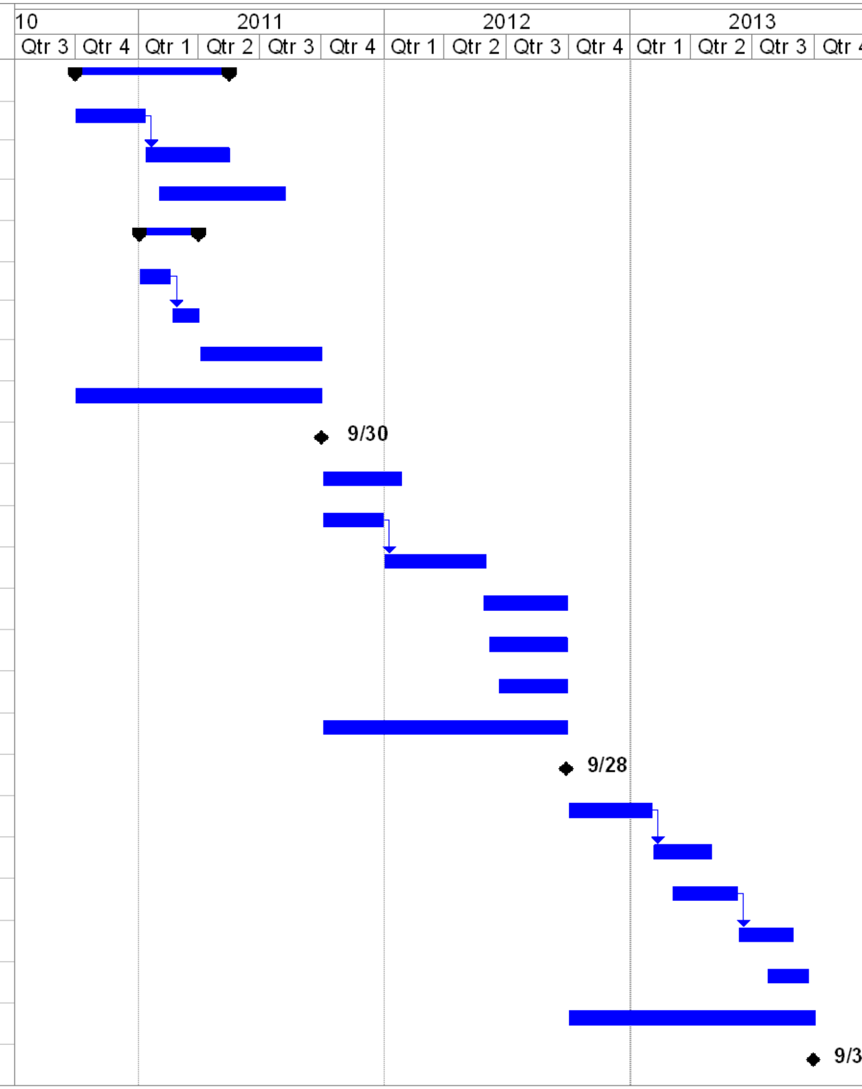


Test Rig to Be Built

- **Design Approach**
  - ✓ **Complete solvent cycle with absorption and regeneration**
- **Process monitoring, control and automation**
- **Data gathering and analysis**

Tasks and Activities

ID	Task Name
1	**Tailor membrane performance**
2	Nano-porous PEEK hollow fiber substrate preparation
3	Surface modification & composite layer formation
4	**Contactor module design optimization**
5	**CO2 capture demonstration**
6	Membrane test unit construction
7	CO2 capture performance demonstration
8	**Absorbent perfomance evaluation**
9	**Phase I project management**
10	**Phase I report**
11	**Design and construction module for regeneration**
12	**Regeneration system design and construction**
13	**Membrane contactor stablity and life testing**
14	**Lab scale regeneration test**
15	**Design bench-scale unit system**
16	**Refined economic evaluation**
17	**Phase II project management**
18	**Phase II report**
19	**Bench scale module and system manufacturing**
20	**Bench scale system shake down**
21	**Site preparation and system installation**
22	**Operation of the system**
23	**Final economic evaluation**
24	**Phase III project management**
25	**Final report**



Plans for Further Testing

- Pilot-scale Field Testing of Membrane Contactor
  - Objective: Process validation and performance testing with realistic feed
- Engineering and Economics
  - Objective: Engineering components, integration into power plant, economic impact of technology on COE
- Demonstration-scale Field Testing of Membrane Contactor
  - Objective: Scale-up testing to obtain engineering parameters for design of full-scale units

Steps After Current Technology Development Project

- Membrane module scale up
- Bench scale testing at pilot scale
- Determine operational challenges and membrane life
- Technology scale up and demonstration
- Detailed process and economic modeling using plant data

Summary

- We have a well laid out plan for successful development of the membrane contactor technology
- Preliminary economics promising
- Membrane contactor technology has many advantages over other competing technologies for carbon capture

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